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METHOD AND APPARATUS OF PERFORMING SAMPLE RATE  
CONVERSION OF A MULTI-CHANNEL AUDIO SIGNAL

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RELATED APPLICATIONS

[01] The application herein (docket number 13587US01) references the following applications having docket numbers 13578US01, 13586US01, 13588US01, and 13589US01 filed on the same day as the application herein (docket number 13587US01) was filed.

FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[02] [Not Applicable]

[MICROFICHE/COPYRIGHT REFERENCE]

20 [03] [Not Applicable]

BACKGROUND OF THE INVENTION

[04] Certain embodiments of the present invention relate to the processing of multi-channel television signals. More specifically, certain embodiments relate to a method and apparatus for performing sampling rate conversion on

digitally decoded BTSC (Broadcast Television System Committee) audio signals.

[05] During the 1980's, the FCC adopted the BTSC format as a standard for multi-channel television sound (MTS).  
5 Typically, the BTSC format is used with a composite TV signal that includes a video signal as well as the BTSC format for the sound reproduction.

[06] The BTSC format is similar to FM stereo but has the ability to carry two additional audio channels. Left plus right (L+R) channel mono information is transmitted in a way similar to stereo FM in order to ensure compatibility with monaural television receivers. A 15.734 KHz pilot signal is used, instead of the FM stereo 19 KHz pilot signal, which allows the pilot signal to be phase-locked to the horizontal line frequency. A double sideband-suppressed carrier at twice the frequency of the pilot transmits the left minus right (L-R) stereo information. The stereo information is DBX encoded to aid in noise reduction. An SAP channel is located at 5 times the pilot frequency. The SAP channel may 10 be used for second language or independent source program material. A professional audio channel may be added at 6.5 times the pilot frequency in order to accommodate additional voice or data.  
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[07] Stereo tuners and demodulator units capable of decoding the BTSC format have been on the market for some time. The front end of the units typically includes analog components or integrated circuit chips. Traditionally, BTSC decoding 5 has been done in the analog domain requiring larger, more expensive implementations that consume a significant amount of power. Previous digital implementations may not be optimized, requiring many clock cycles to perform various processing functions.

10 [08] It is desirable to perform BTSC decoding in the digital domain on a block of an ASIC chip such that the implementation is optimized for reduced complexity and cost. By reducing the complexity, fewer clock cycles are required for processing, and power consumption is also reduced.

15 [09] There are several digital audio output sampling rates that are standard in the industry. The standard digital audio output sampling rates include 32 KHz, 44.1 KHz, and 48 KHz. After decoding any signal component of a composite audio signal down to a common, single sampling rate, it is 20 desirable to be able to output the signal component at any of the three sampling rates described above.

[10] Traditionally, a design to convert from a single sampling rate to any of multiple sampling rates would

require multiple sampling rate conversion schemes, one to handle each desired standard output sampling rate. As a result, duplication of hardware and additional cost and power consumption would be incurred. An efficient 5 implementation to convert from a single sampling rate to any of the standard sampling rates is desired.

[11] Further limitations and disadvantages of conventional and traditional approaches will become apparent to one of skill in the art, through comparison of such systems with 10 embodiments of the present invention as set forth in the remainder of the present application with reference to the drawings.

[12] A need exists for an approach to perform efficient sampling rate conversion in a multi-channel audio signal 15 decoding system by reducing the complexity of the hardware required, therefore reducing cost and power consumption.

#### BRIEF SUMMARY OF THE INVENTION

[13] An embodiment of the present invention provides 20 efficient, low cost sampling rate conversion of a non-standard digital audio signal in a digital multi-channel audio system. Using a single set of low pass filter coefficients, sampling rate conversion from a non-standard

digital audio rate to any of a plurality of standard digital audio rates is accomplished. In such an environment, several stages of digital processing are performed. Efficient processing methods are used to execute the various processing functions in order to reduce clock cycles and addressing to memory.

[14] A method is provided for converting a digital audio signal from a non-standard sampling rate to any of a plurality of standard sampling rates. The digital audio signal at the non-standard sampling rate may include any of a mono signal, a left stereo signal, a right stereo signal, and a SAP signal. The digital audio signal may be previously derived from digital channel demodulation and filtering of a composite digital audio signal including channels such as SAP, L-R stereo, and L+R mono. Techniques of up-sampling, low-pass filtering, and down-sampling are employed to perform sampling rate conversion. A single set of low-pass filter coefficients is used for all of the standard sampling rates.

[15] Apparatus is provided for converting a digital audio signal from a non-standard sampling rate to any of a plurality of standard sampling rates. The digital audio signal at the non-standard sampling rate may include any of a mono signal, a left stereo signal, a right stereo signal,

and a SAP signal. The digital audio signal may be previously derived from digital channel demodulation and filtering of a composite digital audio signal including channels such as SAP, L-R stereo, and L+R mono. The  
5 apparatus comprises a memory storing a single set of low-pass filter coefficients, a low-pass filter using the same single set of low-pass filter coefficients for any of the standard sampling rates, and a linear interpolator allowing non-integer conversion to any of a plurality of standard  
10 sampling rates.

[16] Certain embodiments of the present invention afford an approach to achieve efficient, low cost sampling rate conversion to a plurality of standard sampling rates. Certain embodiments of the present invention also use an  
15 efficient implementation of a single, fixed set of low-pass filter coefficients to achieve any of the plurality of standard sampling rates.

#### BRIEF DESCRIPTION OF THE DRAWINGS

20 [17] Fig. 1 is an illustration of various possible component channels of a composite audio signal that may be decoded to extract a particular audio channel. A final step of the decoding process is sample rate conversion that uses a

single, fixed set of low-pass filter coefficients in accordance with an embodiment of the present invention.

[18] Fig. 2 is a functional block diagram of an apparatus for performing sampling rate conversion from a non-standard sampling rate to any of a plurality of standard audio sampling rates using a single, fixed set of low-pass filter coefficients in accordance with an embodiment of the present invention.

[19] Fig. 3 is an exemplary illustration of low-pass filtering in accordance with an embodiment of the present invention.

[20] Fig. 4 is an illustration of the frequency response of a low-pass filter that is used in the apparatus of Fig. 2 in accordance with an embodiment of the present invention.

[21] Fig. 5 is an exemplary illustration of low-pass filtering and linear interpolation in accordance with an embodiment of the present invention.

[22] Figure 6 is an exemplary illustration of phased filtering in accordance with an embodiment of the present invention.

## DETAILED DESCRIPTION OF THE INVENTION

[23] Fig. 1 is an illustration of various possible component channels of a composite audio signal 10 that may be decoded to extract a particular audio channel. A final step of the 5 decoding process is sample rate conversion that uses a single, fixed set of low-pass filter coefficients in accordance with an embodiment of the present invention.

[24] During the 1980's, the FCC adopted the BTSC format as a standard for multi-channel television sound (MTS). 10 Typically, the BTSC format is used with a composite TV signal that includes a video signal as well as the BTSC format for the sound reproduction.

[25] The BTSC format is similar to FM stereo but has the ability to carry two additional audio channels. Left plus 15 right (L+R) channel mono information 20 is transmitted in a way similar to stereo FM in order to ensure compatibility with monaural television receivers. A 15.734 KHz pilot signal 25 is used, instead of the FM stereo 19 KHz pilot signal, which allows the pilot signal 25 to be phase-locked 20 to the horizontal line frequency. A double sideband-suppressed carrier, at twice the frequency of the pilot, transmits the left minus right (L-R) stereo information 30. The stereo information is DBX encoded to aid in noise

reduction. An SAP channel 40 is located at 5 times the pilot frequency. The SAP channel 40 may be used for second language or independent source program material. A professional audio channel (not shown) may be added at 6.5 times the pilot frequency 25 in order to accommodate additional voice or data.

[26] Fig. 2 is a functional block diagram of an apparatus for performing sampling rate conversion from a non-standard sampling rate to any of a plurality of standard audio sampling rates using a single, fixed set of low-pass filter coefficients in accordance with an embodiment of the present invention. The apparatus 100 comprises a ROM memory 110 storing a set of phased filter coefficients, a low-pass filter 120 performing low-pass filtering of a non-standard digital audio signal 115, and a linear interpolator 130 performing linear interpolation between output samples of the low-pass filter 120. A phased clock signal 140 is used to clock the sampling rate conversion apparatus 100 in order to output samples of a standard audio signal 117 at a standard digital audio sampling rate.

[27] Sampling rate conversion (SRC) is performed on the decoded SAP audio signal, the demodulated mono audio signal (L+R), or the stereo left and right audio signals. In one embodiment of the present invention, the sampling rate of

the demodulated audio signals is 31.64 KHz and is a non-standard sampling rate. Efficiency of preceding decoding functions is achieved, however, by generating all of the demodulated audio signals at the same sampling rate of 31.64  
5 KHz and then performing sampling rate conversion to any of the standard audio sampling rates.

[28] In accordance with an embodiment of the present invention, sampling rate conversion is a process of translating the non-standard audio signal sampling rate of  
10 31.64 KHz to a sampling rate including one of the standard audio output sampling rates of 32 KHz, 44.1 KHz, or 48 KHz. An embodiment of the present invention accomplishes sampling rate conversion by performing a combination of signal up-sampling, interpolation, and signal down-sampling.

15 [29] Up-sampling is the first part of sampling rate conversion and is typically performed by inserting zeros between digital samples of the non-standard digital audio signal 115 to generate a signal at a higher effective sampling rate. The value of the up-sampling factor is  
20 determined by trading off various factors of complexity, cost, and performance. In an embodiment of the present invention, the non-standard digital audio signal 115 is effectively up-sampled by a factor of 64 and filtered with a

low-pass filter having 1152 taps (i.e. using 1152 coefficients).

[30] A problem with up-sampling is that it generates aliasing. Therefore, aliased components appear in the final sampling rate converted signal if the aliased components are not filtered out (or at least greatly reduced). A low-pass filter is used to perform the function of interpolating the up-sampled signal to generate digital sample values that correspond to the up-sampled rate. If a set of low-pass filter coefficients is designed with a cut-off frequency corresponding to approximately  $\pi$  divided by the up-sampling factor or lower, the aliased components are filtered out of (or greatly reduced in) the resultant signal before down-sampling is performed. The vast majority of the audio information is below 12 KHz. In an embodiment of the present invention, the cut-off frequency of the low-pass filter is designed to be at 13 KHz. The cut-off frequency of 13 KHz reduces the aliased components and simplifies the filter design.

[31] A feature of one embodiment of the present invention with respect to sampling rate conversion is that any of the resultant audio output signals (SAP out, mono out, left out, right out) may be converted to any one of the three standard

audio output sampling rates listed above by using the same set of low-pass filter coefficients 110 in the SRC conversion process performed by apparatus 100.

[32] To illustrate the up-sampling and filtering process,

5 Fig. 3 shows a simple example of inserting zeros in an original signal 200 at, for example, 3 Hz to generate an up-sampled signal 210 at 9 Hz (i.e. up-sampling factor is three). The up-sampled signal 210 is passed through a simple 6-tap filter 220 having a fixed set of filter  
10 coefficients (which are symmetric in the example) and generating a set of output samples 230. The output samples are at the up-sampled rate of 9 Hz. Typically, the coefficient values of the filter are scaled or normalized such that the resultant output values are an interpolated representation of the input values. If a down-sampling  
15 factor of, for example, two is then selected, the resultant output sampling rate is 4.5 Hz and the corresponding output samples are those samples 240 shown in the boxes in Fig. 3. By designing the filter coefficients correctly as described  
20 above, the unwanted aliased components are filtered out (or greatly reduced). In an embodiment of the present invention, the low-pass filter uses 1152 taps or coefficients having the frequency response 300 shown in Fig.  
4.

[33] If the desired final sampling rate in the example of Fig. 3 is instead 6 Hz, then the filtered signal is down-sampled by a factor of 1.5 (i.e.  $9 \text{ Hz}/1.5 = 6 \text{ Hz}$ ). However, down-sampling by a factor of 1.5 (a non-integer value) means 5 sometimes selecting samples between the filtered output samples 230. Since there are no samples to choose from between the filtered output samples, linear interpolation is performed to make up samples where needed to achieve down-sampling by a factor of 1.5 yielding a sampling rate of 6

10 Hz.

[34] Fig. 5 illustrates the current example of sampling rate converting from 9 Hz to 6 Hz using linear interpolation. The filtered output sequence 230 is the same as before but now samples must be selected between certain output samples 15 because the down-sampling factor is not an integer value in the current example of Fig. 5. The arrows 250, illustrate where interpolation must be performed. The boxes indicate samples that may be used directly. In the current example, the linear interpolator 130 performs a simple averaging of 20 the values on either side of the interpolated points to yield the output sequence 260 at the desired 6 Hz rate. The values of 9.5, 8.5, and 10 are the interpolated values.

[35] In an embodiment of the present invention, sampling rate conversion is being performed on a non-standard digital

audio signal 115 of 31.64 KHz to convert to any of the standard audio sampling rates of 32 KHz, 44.1 KHz, and 48 KHz. Since the effective up-sampling factor is always 64, the down-sampling factor will never be an integer value and, 5 therefore, linear interpolation is used to generate the standard digital audio signal 117. The down-sampling factor corresponding to the standard audio sampling rates are then

	<u>standard sampling rate</u>	<u>down-sampling factor</u>
	32 KHz	63.28
10	44.1 KHz	45.917
	48 KHz	42.186

[36] Since, in an embodiment of the present invention, the up-sampling factor is always 64 and the sampling rate of the standard digital audio signal 117 is always greater than the 15 sampling rate of the non-standard digital audio signal 115, a single set of low-pass filter coefficients may be used. There is no need for a dedicated up-sampling rate or filter for each standard sampling rate.

[37] To simplify the implementation of an embodiment of the 20 present invention, instead of using a single 1152-tap filter operating on an up-sampled signal, the 1152 tap coefficients are re-arranged into 64 phases of 18 coefficients each. The non-standard digital audio signal 115 is then operated on by

the low-pass filter 120 with the various phases of coefficients as needed. Fig. 2 illustrates the phased filtering implementation.

[38] Figure 6 illustrates a simple example of phased filtering to simplify the sampling rate conversion implementation. The original filter 220 is now divided up into three phases as shown in Fig. 6. There are three phases because the up-sampling factor is three. Certain taps of the filter 200 are shown having black dots in certain corners to make it clear which taps are used to create the phased filters in Fig. 6. Every third tap is selected from the original filter 220 to generate the phased filters. The original input signal is operated on by each of the three phases yielding the filtered output samples 350 as shown in Fig. 6. If the desired output sampling rate is again 4.5 Hz as before, the down-sampling factor is again two. To generate the desired 4.5 Hz output signal, the boxed samples of the output samples 350 of the various phases shown in Fig. 6 are selected.

[39] It may be seen that the selected output samples in Fig 6 are the same as those output samples selected in Fig. 3 for the 4.5 Hz sampling rate. Each successive output sample is generated by a different filter phase. The first sample is from phase 1 (310), the second sample is from phase 2

(320), the third sample is from phase 3 (330), and the fourth sample is again from phase 1 (310). This rotating cycle of generating the output samples at a rate of 4.5 Hz from the different phases means that only one filter phase  
5 (having only two-taps) needs to be calculated for a given output sample. Also, the non-standard digital audio signal  
115 is effectively up-sampled by duplication instead of inserting zeros. The filtered signal is effectively down-sampled by applying the appropriate phased filter for the  
10 appropriate output sample. By implementing sampling rate conversion according to the configuration of Fig. 2 as illustrated by the simple example of Fig. 6, great efficiencies in hardware and computation are achieved. It should be noted that, for the example of converting to the  
15 output sampling rate of 6 Hz, two phased filtered outputs are generated for each 6 Hz output sample, and linear interpolation is performed between the two filtered samples. Still, this is a great improvement in having to up-sample by inserting zeros and operating on all 6-taps for every output  
20 sample generated.

[40] In an embodiment of the present invention, the 1152 coefficients are divided into 64 phases of 18 coefficients each. A given 18-tap phased filter is generated by selecting every 64<sup>th</sup> coefficient from the original 1152 tap

filter. To generate an output sample of the standard digital audio signal, only two 18-tap phases of the 64 are used along with linear interpolation. The 64 phases are rotated through to generate successive output samples at any 5 of the standard sampling rates. The next pair of phases to be used to generate the next output sample depends on the effective down-sampling rate currently selected and the current phase of the standard digital audio signal. Periodically during the generation of the standard digital 10 audio signal 117, four phases are selected and 2 output sample points are generated at the same time in order to maintain the desired standard sampling rate.

[41] For an embodiment of the present invention described, the interpolated points do not always fall exactly in 15 between two filtered points. For any given pair of filtered points to be interpolated, there is a corresponding accumulated interpolation ratio that is generated by the linear interpolator 130. As generation of successive output samples proceeds, the linear interpolator increments the 20 accumulated interpolation ratio, for the current phase of the standard digital audio signal being generated, and applies the current interpolation ratio in the interpolation process. For example, for the standard sampling rate of

44.1 KHz, the interpolation ratio increment is  $(4410 - 3164)/3164 = 1246/3164$ .

[42] Therefore, for a first output sample of the standard digital audio signal 117, the linear interpolator will interpolate between two filtered output samples, weighting the one filtered output sample by the current accumulated interpolation ratio of  $1246/3164$  and the other filtered output sample by  $1-(1246/3164)$ , which is one minus the current accumulated interpolation ratio. For the very next output sample, the accumulated interpolation ratio is incremented by  $1246/3164$  to  $2492/3164$  and the linear interpolator generates the next output sample based on  $2492/3164$  and  $1-(2492/3164)$ . As a result, interpolation is always done at the appropriate distance between the appropriate two filtered output samples. For the other standard output sampling rates of 32 KHz and 48 KHz, the interpolation ratio increments will be  $(3200-3164)/3164 = 36/3164$  and  $(4800-3164)/3164 = 1636/3164$ , respectively.

[43] The various elements illustrated in Fig. 2 may be combined or separated according to various embodiments of the present invention within the ASIC chip or may be separated and implemented over more than one chip.

[44] In summary, certain embodiments of the present invention use a single set of low-pass filter coefficients to perform sampling rate conversion from a non-standard sampling rate to any of a plurality of standard sampling rates. An efficient implementation employing phased filtering techniques is used to perform sampling rate conversion.

[45] While the invention has been described with reference to certain embodiments, it will be understood by those skilled in the art that various changes may be made and equivalents may be substituted without departing from the scope of the invention. In addition, many modifications may be made to adapt a particular situation or material to the teachings of the invention without departing from its scope. Therefore, it is intended that the invention not be limited to the particular embodiment disclosed, but that the invention will include all embodiments falling within the scope of the appended claims.